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13. ABSTRACT *(Maximum 200 words)*

When computer-generated imagery is presented on a raster display device, the spatiotemporal representation of a given dynamic scene varies with the update of the image generator and the refresh pattern of the display device. The effects of these variables on form perception were examined in 3 experiments. In Experiment 1, observers were instructed to maintain a steady fixation during 267-ms motion sequences. Target shape, target velocity (4.7, 9.4, and 18.8 deg/s; right to left and left to right), image update rate (30 and 60 Hz), and raster pattern (interlaced and noninterlaced) were varied orthogonally. Identification responses indicated that the temporal interval between successive fields of an interlaced display tended to be perceived as a spatial interval. The probability and extent of this temporal-to-spatial conversion (TSC) declined as target velocity increased. In Experiment 2, observers were instructed to track the target in 30 Hz, interlaced displays of 3 durations (133, 267, and 533 ms). Under these conditions, complete TSC was the predominant percept for all velocities (4.7 to 18.8 deg/s) at the longest sequence duration. In Experiment 3, observers were instructed to track the target in non-interlaced displays. Sequence duration (267, 533, 800, and 1,067 ms), image update rate (15, 30, and 60 Hz), target velocity (4.7, 9.4, and 14.1 deg/s) and direction of target-surround contrast (dark on light, as in Experiments 1 and 2, and light on dark) were varied. Observer responses indicated that TSC is not limited to interlaced presentations: Multiple (up to 2 for 30 Hz and 4 for 15 Hz) replicas of the target were seen to move in unison. The extent of TSC varied with direction of contrast as well as with sequence duration and target velocity.

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PREFACE

This report is based on research performed at the Aircrew Training Research Division of the Armstrong Laboratory, Williams Air Force Base, Arizona. It is part of an ongoing effort to improve the visual systems of flight simulators. The particular objective of this project was to assess the effects of image update rate and display interlacing on the perception of small targets in horizontal motion.

The work was conducted by the University of Dayton Research Institute under Contract No. F33615-90-C-0005, Work Units 2743-2517, Flying Training Research Support, and 1123-32-01, Visual Systems Display Functions Measurement. The Technical Monitors were Drs Elizabeth L. Martin and Byron L. Pierce, and the Contract Monitor was Capt Claire A. Fitzpatrick.

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TEMPORAL AND SPATIAL FACTORS AFFECTING THE PERCEPTION OF COMPUTER-GENERATED IMAGERY

SUMMARY

The visual systems of most flight simulators consist of a raster display of computer-generated images. Image generators (IGs) differ in the rate at which they can compute new images, and some IGs respond to overload problems by reducing their nominal rate. The typical display device has an interlaced raster-scan pattern (i.e., only 1 of 2 fields in a frame is refreshed during a given vertical scan), such that the frame rate is only half the field (vertical refresh) rate.

In such systems, object motion is represented by a sequence of images in which the position and spatial form of the object is suitably varied. The exact spatiotemporal representation of a given object trajectory depends upon the update rate of the IG and the raster pattern and refresh rate of the display device.

The results of a series of experiments indicate that these variables affect the perceived form of an object in horizontal motion. If the image update rate is less than the display refresh rate, the temporal intervals between repeated presentations of a target (or target component) at a given location tend to be seen as spatial intervals. When this temporal-to-spatial conversion (TSC) is complete, the earlier representations appear advanced by the distance the object would have traveled if it were in constant velocity motion. To avoid such perceptual distortions, the update rate of an IG should equal the refresh rate of the display device.

INTRODUCTION

Image generation systems are now capable of producing quite complex images for flight simulators and other interactive, real-time applications. In such systems, an IG computes a sequence of digital arrays, each of which represents the visual world at a particular point in time. These digital-image values modulate the output of 1 to 3 electron guns in a raster display device.

The electron beams of raster-scan displays trace a fixed pattern of horizontal lines, from left to right, from top to bottom. The order in which these lines are scanned depends upon whether the display raster is interlaced or noninterlaced. When a raster is interlaced, a frame (all of the lines) is divided into 2 fields: one consisting of even numbered lines and the other of odd numbered lines. The lines of 1 field are presented sequentially during 1 vertical scan; the lines of the other field are presented during the next vertical scan. In contrast, when a raster is noninterlaced, all the lines in a frame are presented during each vertical scan (refresh) period.

The IG and the display device operate concurrently. While 1 image is being presented, the next image is being calculated. The rate at which new images are generated (the image update rate) is not, however, directly dependent upon the refresh characteristics of the display device. An IG coupled with an interlaced display can update once every field (60 Hz on a standard system) or once every frame (30 Hz). Similarly, an IG with a noninterlaced display can update every frame (60 Hz) or every other frame (30 Hz). Some IGs update at less than 30 Hz, in which case an image is displayed repeatedly until computation of the next image is completed.

Relative movement of an object is portrayed by appropriate differences over frames or fields in the size, shape, and location of its spatial representation. The exact sequence of images depends upon the update rate of the IG and the raster pattern of the display device as well as on the movement of the object. For example, if an object is moving across the field of view at a constant "virtual" velocity, the image update rate determines the spatial interval between displayed locations. Regardless of velocity, the ratio of the refresh rate of the display to the update rate of the IG determines the number of times a representation of the object is presented at each location. The raster pattern determines the nature of that representation: On a noninterlaced system, a complete representation of the object is presented during each refresh; on an interlaced system, in contrast, each field contains only a partial representation of the object, and a field time (typically, 16.7 ms) separates the display of spatially contiguous lines--regardless of the update rate and thus whether the 2 fields of a frame depict the same or different moments.

Although it is well established that a human observer tends to perceive continuous motion when presented with a suitable "stroboscopic" motion stimulus (i.e., a temporal sequence of static images), there has been little systematic investigation of the perceptual consequences of image update rate and display interlacing. Given the effects of these variables on the spatiotemporal representation of a moving object, it would be surprising if form and motion perception were invariant.

Using an oscilloscope (i.e., nonraster) display, Hempstead (1966) varied the "frame rate" (image update rate) for horizontal stroboscopic-motion sequences in which the target was a vertical line moving a constant virtual velocity. For conditions corresponding to a 30-Hz update rate and a 60-Hz noninterlaced display, he reported that an observer's percept depended upon whether the target was or was not visually tracked (although eye position was apparently not monitored). If the observer fixated a stationary spot on the screen, the perceived motion was not continuous, and 2 or more of the discrete presentations were simultaneously visible. In contrast, if the observer tracked the target, a pair of lines appeared to move continuously across the screen. With regard to the latter, double image, Hempstead proposed that the smooth pursuit movement of the eyes matched the virtual velocity of the target and that, as a result, the 2 presentations of each frame were imaged on different retinal loci. The spatial percept was thought to be a replica of the retinal image, with the spatially leading line resulting from the temporally leading presentation of each frame (see also Braunstein & Coleman, 1966; Hsu, 1985; and Stenger et al., 1981).

A seemingly comparable conversion of temporal to spatial intervals, in the *absence* of pursuit eye movements, has been reported by Burr (1979), Fahle and Poggio (1981), and Morgan and his colleagues (Morgan, 1980; Morgan & Watt, 1982, 1983). For relatively low-velocity, horizontal stroboscopic motion, they have found that the 2 halves of a vernier acuity target (i.e., 2 vertical line segments, 1 above the other) are perceived as horizontally offset if they occupy perfectly aligned stations (displayed locations) at slightly different times. The temporally leading half appears spatially advanced by about the distance it would have traveled during the ensuing temporal interval.

This discrepancy in the role of pursuit eye movements may be attributable to differences in the spatial interval between displayed locations (i.e., in the interstation distance) or to differences in the spatial characteristics of the target. Although Hempstead provided very little detail about his experimental procedures or motion displays, his "example" station distance was approximately 1 degree. The results of a study by Morgan and Watt (1983) suggest that TSC in the absence of visual pursuit may be limited to motion sequences in which the distance between stations is appreciably smaller than one deg. It may be, then, that visual pursuit eye movements are critical for TSC during stroboscopic motion sequences if the interstation distance is relatively large but not if it is relatively small. On the other hand, the target in Hempstead's research was a single line, whereas Burr and Morgan used 2 lines that occupied different locations along the dimension orthogonal to the direction of motion. Perhaps TSC does not occur if successive presentations are imaged on the same retinal locus.

The evidence for TSC has obvious implications for the raster display of computer-generated imagery. When the update rate of the IG is less than the refresh rate of the display (the field rate for an interlaced display or the frame rate for a noninterlaced display), a representation of a moving object is presented during each of the 2 (or more) refresh periods associated with each frame. If these temporal intervals are perceived as spatial intervals, form information will be distorted or degraded. On the other hand, when the update rate equals the refresh rate and the display is interlaced, the object representations at each spatial location are incomplete, and a failure of TSC would result in form distortion.

EXPERIMENT 1

This experiment was designed to explore the effects of image update rate, interlacing, and interstation distance on form perception when observers are instructed to maintain a steady fixation. To assess the generality of any observed effects and to ensure that observers were uncertain as to the shape determining the display on any given trial, the spatial form of the target was also varied.

In contrast to prior research (e.g., Burr, 1979; Fahle & Poggio, 1981; Hempstead, 1966; Morgan & Watt, 1982; 1983), the pixels representing a target were dark, and the surrounding area was light. Several considerations led to the selection of this display mode: (a) Targets in flight simulators are often darker than the surrounding field; (b) phosphor persistence would not contribute to the perceived spatial form; and (c) evidence of TSC would eliminate the possibility that this phenomenon is specific to stroboscopic sequences of light lines against a dark background.

The duration of the stroboscopic-motion sequence was chosen to be long enough for the development of TSC (Morgan & Watt, 1982) but not so long that observers would experience great difficulty maintaining a steady fixation. To prevent undue influence of the final field(s) of the motion sequence, a backward-masking procedure was used. With this procedure, a complex patterned stimulus (mask) is presented immediately following a target stimulus. If suitably chosen, the second stimulus interferes with or terminates the perceptual processing of the first stimulus (Breitmeyer, 1984; Turvey, 1973).

Method

Observers

Three men and 2 women, ranging in age from 23 to 45, served as observers. All observers had normal or corrected-to-normal vision and were uninformed with respect to the purpose of the experiment.

Apparatus

A Digital Equipment Company PDT 11/150 microcomputer was used to control the experimental sequence and to record subject responses. The visual displays were generated on a Hewlett-Packard 2648A Graphics Terminal, which has a 60 Hz, noninterlaced cathode-ray tube (CRT) equipped with P4 phosphor. A graphics memory of 720x360 determines the addressability of this device in its normal mode. For the experiments reported here, however, a hardware zoom was used to display portions of the graphics memory in increased size. (Specifically, one-ninth of the graphics memory was displayed with a zoom size of 3.) This feature provided the means by which different images could be presented on successive vertical scans in spite of the relatively slow speed of this IG.

A VOTAN VTR6050 Series Voice Terminal added voice input and output to the system. The terminal was programmed to accept spoken words or phrases and to output both prerecorded messages and strings of keystrokes.

Observers sat in a dimly illuminated room and viewed the display screen from a distance of approximately 70 cm. This distance was maintained by an opaque, black hood affixed to the front of an enclosure for the graphics terminal. The screen was masked so that only a 15.5 degree horizontal x 8.2 degree vertical area was visible.

Visual Displays

Dark-on-light displays were created by setting the alphanumeric memory of the graphics terminal to inverse video. With the hardware zoom set to 3, the dark pixels appeared square and separated from each other by thin lines. The center-to-center distance between pixels was approximately 4.7 arc min.

At the beginning of each trial, the center of the screen and of the ensuing motion sequence was marked by 2 points (single, dark pixels) separated vertically by 5 pixel spaces. When the observer gave the appropriate voice command, these points were replaced by a blank, light screen. After approximately 600 ms, a 267 ms (16 vertical scans) motion sequence was presented. This motion sequence was immediately followed by a mask which remained on the screen throughout the response period.

The target forms for the motion sequences were composed of 4 pixels, a 3-pixel horizontal line with a single pixel positioned over the left, center, or right pixel (Fig. 1, top). The masks consisted of 61 full rows of pixels, centered vertically. Each mask was constructed by "tiling" with an 8x8 pattern consisting of 32 light and 32 dark pixels arranged in like-luminance, horizontal runs of 1 to 3 (Fig. 1, bottom). Trial-to-trial variation resulted from a random reordering of the 8 rows within the basic pattern.

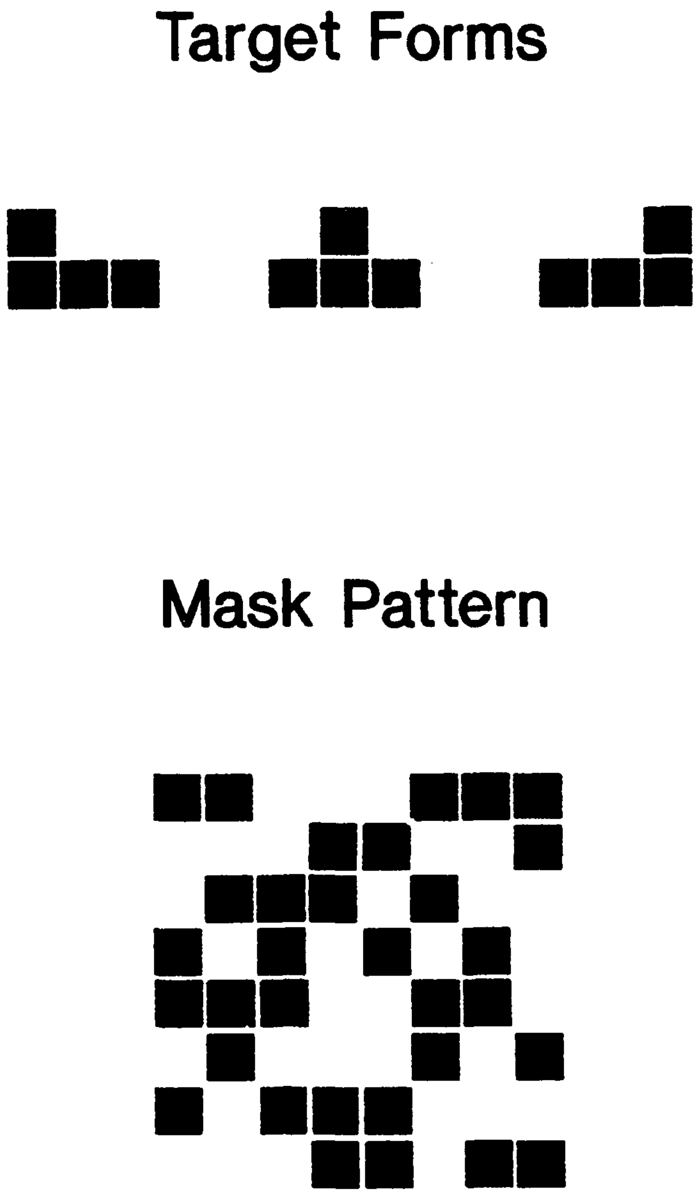

Figure 1. Target Forms and the 8x8 Pattern Used to Construct the Masking Stimulus in Experiment 1.

The target forms were displayed in either a noninterlaced or an interlaced mode. Interlacing was simulated by presenting either the top pixel or the bottom 3 pixels, but not both, on a given vertical scan. The part of the form presented first was varied systematically. There were 3 raster patterns: noninterlaced, interlaced--top first, and interlaced--bottom first.

The nominal position of the target was displaced, either left-to-right or right-to-left, at a rate of 60, 120, or 240 pixels/s (1, 2, or 4 pixels every refresh). Given a pixel width of 4.7 arc min at the viewing distance of 70 cm, these displacements represented virtual velocities of approximately 4.7, 9.4 and 18.8 degrees/s. (The corresponding velocities for a 7.5-m aircraft at a range of 1.6 km would be roughly 300, 600, and 1,200 knots.)

The actual position of the target was updated at a rate of either 30 Hz or 60 Hz. For the noninterlaced display mode, an image update rate of 60 Hz meant that the entire form was written once at each *station* (positions separated horizontally by 1, 2, or 4 pixels, depending upon the velocity), whereas an update rate of 30 Hz meant that the entire form was written twice at every other station (positions separated by 2, 4, or 8 pixels). To simulate an interlaced display with an image update rate of 60 Hz, either the top or bottom of the form was written at each station. To simulate an interlaced display and an update rate of 30 Hz, the entire form was written at every other station, with 16.7-ms intervals separating the presentations of the two parts of the form.

Response Set

During preliminary sessions, observers frequently reported seeing 7 different spatial forms: The top pixel appeared to be positioned (a) to the left or right of the bottom line of pixels; (b) over the left, center or right bottom pixel; or (c) halfway between the left and center or right and center pixels. Consequently, the response set included 7 descriptions of the apparent position of the top pixel: "off-on-the-left," "left," "slightly left," "center," "slightly right," "right," and "off-on-the-right." An eighth response option, "multiple forms," allowed observers to indicate that the relative position of the top pixel appeared to change or move during the trial. Observers were also allowed to say "missed" when they felt that they had gained insufficient information for form categorization.

Procedure

Observers were tested individually for 8 sessions. The first 3 sessions were considered practice. During an observer's initial session, the Voice Terminal was "trained" to recognize that observer's speech. During testing, observers initiated a trial by

saying "next"; a validation procedure allowed them to correct any response or recognition errors.

A different random order of the 108 possible motion sequences (3 interlacing conditions x 2 update rates x 3 target forms x 3 speeds x 2 directions) was presented during each session. The observers were instructed to fixate the center of the screen during a trial and to report any percepts that failed to correspond to the designated response alternatives. If an observer responded to a particular motion sequence with the word "missed," that combination of variable levels was presented on a randomly determined trial later in the testing session.

Results

Responses in Accord with Stimulus Form

Each response was initially categorized as a correct or incorrect identification of the target form that had determined the motion sequence. These data were subjected to a repeated- measures analysis of variance. The alpha level was set equal to .01.

In this analysis, the main effects of raster pattern and target velocity were significant as were the raster pattern x update rate, velocity x update rate, and raster pattern x update rate x velocity interactions (Table 1).

Table 1. Percentages of Responses in Accord with the Target Form in Experiment 1

	Target Velocity (in pixels/s)		
System Parameters	60	120	240
60-Hz Update Rate			
Noninterlaced	95	84	67
Top First	72	26	7
Bottom First	80	32	3
30-Hz Update Rate			
Noninterlaced	95	89	91
Top First	2	16	51
Bottom First	2	7	27

Consider first the data for a target velocity of 60 pixels/s (Table 1, Column 1). When the update rate was 60 Hz and the display was noninterlaced, the perceived form matched the target form on 95% of the trials. Accuracy was only moderately lower (72% and 80%) for the 60 Hz interlaced conditions. When the update rate was 30 Hz, on the other hand, identification accuracy dropped from 95% for the noninterlaced displays to essentially zero for the interlaced displays. Thus, if the display was interlaced, the target form was not perceived correctly when its component parts were displayed in veridical spatial alignment on successive fields, but was usually perceived correctly when its parts were separated by a spatial interval that corresponded to the distance the target would have traveled during the 16.7 ms.

With a 60 Hz update rate, identification accuracy decreased as target velocity increased. This pattern was shown for both the noninterlaced and interlaced display modes, although the decline was greater for the latter. In contrast, with a 30-Hz update rate, identification accuracy remained high across target velocities when the display was noninterlaced and increased with target velocity when the display was interlaced. Finally, for the 30-Hz interlaced displays, the percentage of responses in accord with the target form was less when the bottom part of the form was written first than when the top part was written first.

Response Distributions

As indicated in Table 1, when the display was noninterlaced only the 60 Hz, high velocity sequences resulted in a substantial number of responses that were not in accord with the target form. The response distributions for these conditions revealed that most of the misidentifications involved a slight (one-half to one pixel) displacement of the bottom line *in* the direction of motion.

For the interlaced displays, responses in accord with the target form were mainly limited to the lowest velocity, 60 Hz sequences. To summarize the reported percepts for the other interlaced conditions, each position response was assigned a numeric code reflecting the displacement of the top pixel from the center position. "Off-on-the-left" and "off-on-the-right" responses were treated as 2 pixels to the left and right of center, respectively. "Slightly left" and "slightly right" were treated as half-pixel steps. (Responses indicating a changing form were infrequent and were not considered in this analysis.) The response for each trial was then scored relative to the target form, the direction of motion, and the part of the form written first. For example, if the target form had the top pixel on the left and was moving from left to right, a "center" response was coded as a +1 if the top pixel was written first and as a -1 if the bottom pixels were written first.

The possible scores ranged from -3 (a 3-pixel displacement, of the part written first, against the direction of motion) to +3 (a 3-pixel displacement, of the part written first, in the direction of motion). However, because the most extreme response options specified only that the top pixel was to the left or right of the bottom line, not by how much, the full range of scores was not possible for any stimulus form and direction-of-motion combination. For example, if the target form had the top pixel on the left, the movement was from left to right, and the top pixel was written first, the possible scores ranged from -1 ("off-on-the-left") to +3 ("off-on-the-right"). This restriction meant that for the higher velocities, complete and partial TSC would sometimes be represented by the same response.

Figure 2 presents the response distributions, coded as described, for the 60 Hz, interlaced motion sequences. In these sequences, it will be recalled, the part of the form written during the first field of each 2-field frame was actually displaced (relative to the part written second) 1, 2, or 4 pixels against the direction of motion. Although the amount of perceived displacement cannot be fully recovered from these data, the distribution of responses that would correspond to what was actually written during a frame can be specified for each target velocity: For the slowest velocity, all of the responses would correspond to a displacement of -1; for the intermediate velocity, 67% of the responses would correspond to a displacement of -2 and 33% to a displacement of -1; for the highest velocity, 33% of the responses would correspond to displacements of -3, -2, and -1, respectively.

Comparison of the panels in Figure 2 suggests an orderly progression, with target velocity, from a percept determined primarily by the target form to one determined primarily by the form as written during successive pairs of fields. Note, however, that most of the apparent displacements for the Bottom First distributions were positive rather than negative. In this case, the reported percepts reflected the form defined by the second field of one frame and the first field of the following frame. Thus, fields tended to be combined (within frames for Top First presentations; across frames for Bottom First presentations) so that the bottom line led rather than trailed the top pixel. The relatively low frequency of 1-pixel displacements at the highest target velocity suggests that the percepted grouping of components may have also been influenced by spatial proximity: A series of fields that could be perceived as an object with the bottom line leading could also, for certain motion sequences, be perceived as a more compact object with the bottom line trailing. Whereas a response based on the former sequence would be coded as a 1-pixel displacement, a response based on the latter sequence would be coded as a 3-pixel displacement in the opposite direction. Examination of the actual responses for each high velocity sequence tended to support this interpretation: Responses were much more

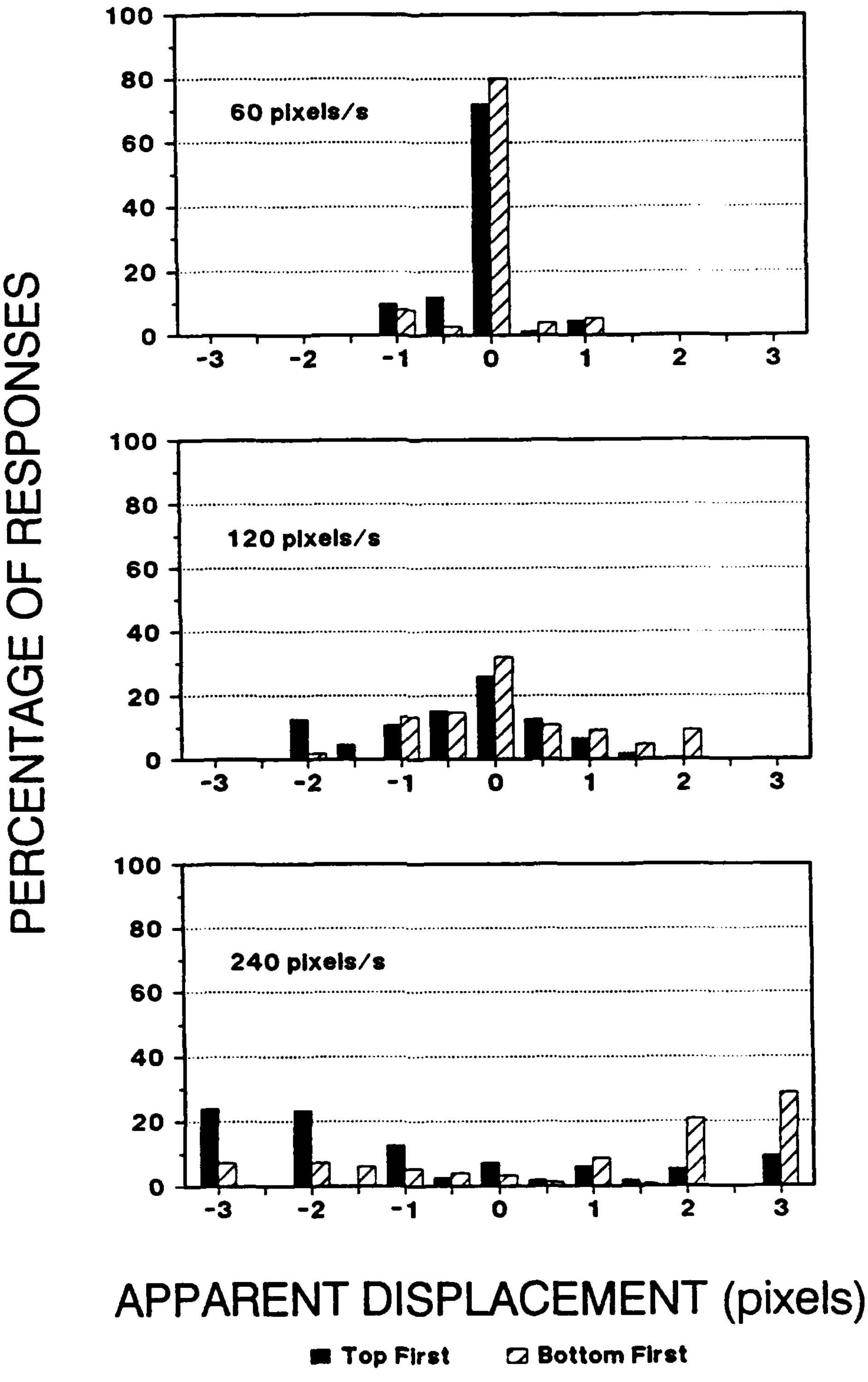

Figure 2. Apparent Displacement for the Interlaced Displays with a 60-Hz Image Update Rate in Experiment 1. Displacement is for the part of the target form displayed during the first field, relative to the direction of motion.

consistent when the aforementioned cues (bottom leading and component proximity) were in accord than when they were in conflict.

Figure 3 presents the apparent displacement data for the interlaced display modes when the image update rate was 30 Hz (i.e., when the 2 parts of the target form were presented in veridical spatial alignment but separated by 1 field time). For the slowest target velocity, that part of the form displayed during the first of the 2 fields usually appeared to be displaced in the direction of motion by 1 pixel, the distance it would have traveled during the 16.7 ms separating the presentations of the 2 parts. For the slowest velocity, then, TSC was complete. In contrast, when the target velocity was 120 pixels/s, only 26% of the responses corresponded to a 2-pixel displacement, the distance the target would have traveled during the interval separating the 2 fields. This percentage was well below that possible (67%) with the available response options. Moreover, approximately 22% of the responses indicated apparent displacements of zero or one-half pixel. Such responses were even more likely when the target velocity was 240 pixels/s. For this velocity, there was essentially no evidence of complete TSC. Finally, for both of the 2 higher target velocities, the reported displacement when the bottom part of the object was presented first was greater than that when the top was presented first.

Discussion

In Experiment 1, observers attempted to maintain a steady fixation during 267-ms displays of computer-generated motion sequences. Under these conditions, TSC occurred if the raster pattern was interlaced and the virtual velocity was low (4.7 degrees/s): The perceived form matched the velocity-determined distortion of the target form when the image update rate equaled the _frame_ rate (30 Hz) and matched the target form itself when the update rate equaled the _field_ rate (60 Hz). For the interlaced displays of higher target velocities, the apparent spatial displacement, when present, tended to be less than that associated with complete conversion. Moreover, the higher the velocity, the more often the reported percept corresponded to the arrangement of components in successive fields: For the 30-Hz update rate, responses were increasingly in accord with the target form; for the 60-Hz update rate, responses were increasingly in accord with either the 2 fields within a frame or the second field of 1 frame and the first field of the following frame.

There was no evidence of TSC when the display was noninterlaced, although it is possible that observers failed to report double images because appropriate response options were not provided. This lack of TSC for temporal intervals separating overlapping presentations of the same spatial form suggests that the effect occurs only when successive stimuli occupy different

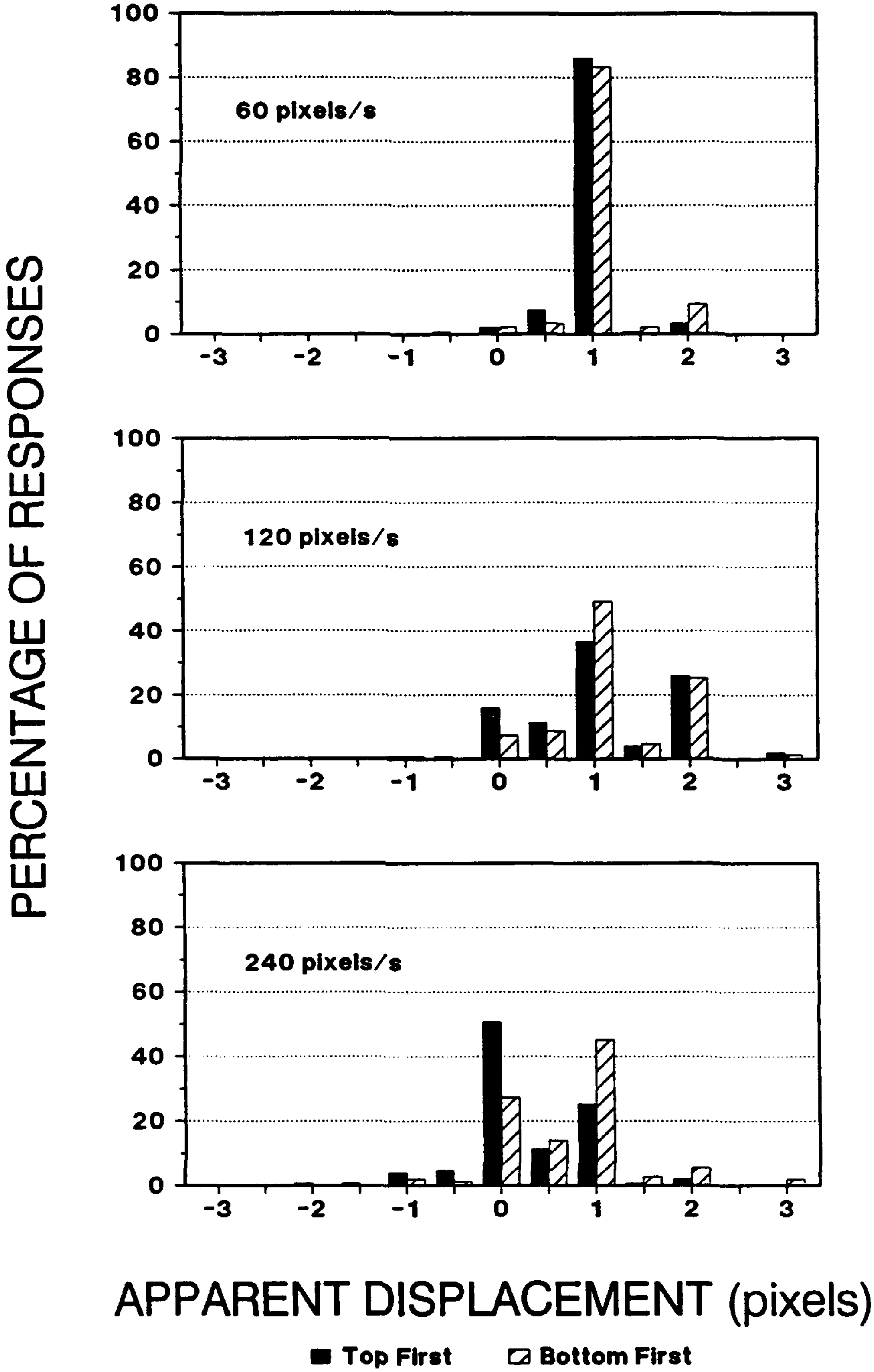

Figure 3. Apparent Displacement for the Interlaced Displays with a 30-Hz Image Update Rate in Experiment 1. Displacement is for the part of the stimulus form displayed during the first field, relative to the direction of motion.

environmental or, assuming that observers successfully maintained fixation, different retinal positions.

Although the percept for a given motion sequence was determined primarily by the temporal and spatial intervals between the 2 component forms, the spatial characteristics of the components themselves (e.g., size or position within the configuration) also had an effect: (a) For the noninterlaced displays with a 60-Hz update rate, the identification errors for the highest target velocity tended to involve small displacements of the bottom line in the direction of motion; (b) for the interlaced displays with a 30-Hz update rate (see Fig. 3), the apparent displacement of the part written first was greater when it was the bottom line than when it was the top pixel; and (c) for the interlaced displays with a 60-Hz update rate, the perceived forms for the higher target velocities tended to have the larger, bottom component in the leading position.

One possible explanation for at least the first 2 findings is provided by data which suggest that processing speed decreases as spatial frequency increases (Breitmeyer, 1975; Lupp, Hauske, & Wolf, 1976). Although each of the 2 component forms had a broad spatial-frequency spectrum, the 3-pixel line contained more power in the lower frequencies. If spectral differences resulted in different component-processing speeds, with an advantage for the larger component, then the effective presentation times would have differed and TSC could have acted to advance the apparent relative position of the bottom line. Size or spatial-frequency-determined differences in processing time could also have contributed to the tendency to perceptually combine fields of the 60 Hz, interlaced sequences so that the bottom line was leading the top pixel.

Because the display rate was fixed in this experiment, distance between successive presentations and the virtual velocity of the target covaried. Thus, the effects attributed to target velocity could have been due either to velocity per se or to the size of the interstation distance. This distinction is of applied as well as theoretical importance. The practical question, as far as flight simulation is concerned, is whether increasing the image update and display rates of an interlaced system, which would in turn reduce the interstation distance for a given target velocity, would increase the velocities for which TSC is found.

Data relevant to this issue are provided by acuity-target experiments in which the display device did not refresh at a predetermined rate. Two types of tasks have been presented. In the first type, the line segments were presented in spatial alignment but with a variable temporal offset. Observers indicated the perceived direction of spatial offset (Fahle & Poggio, 1981; Morgan & Watt, 1983). Estimates of the threshold for detection of the temporal offset were expressed in terms of the corresponding virtual spatial displacement (i.e., as the distance the leading

line would have traveled during the ensuing temporal interval if the target were moving at a constant velocity). In the second type, observers adjusted the temporal offset (between the 2 lines segments) so that it compensated for a fixed spatial offset (Fahle & Poggio, 1981) or the spatial offset so that it compensated for a fixed temporal offset (Morgan, 1980).

These studies do not, however, present a consistent picture of the determinants of TSC. This inconsistency may have resulted from certain methodological problems: In the threshold studies, observer responses may sometimes have reflected perception of apparent motion (orthogonal to the direction of target motion) between the 2 line segments rather than or in addition to an apparent spatial offset (Morgan & Watt, 1983); in the compensation studies, the failure to provide a masking stimulus could have caused the final displays of a sequence, and thus the spatial arrangement of the line segments, to be given undue perceptual weight. On the other hand, TSC may not be limited by just 1 factor. The vernier-target experiments differed in the values of a number of potentially important variables: the duration of the motion sequence and thus the number of stations associated with a given distance-velocity combination; the sizes of the interstation and target-display intervals; and the direction (horizontal vs. vertical) and position (centered around vs. terminating at the fixation point) of the motion path. Moreover, although an attempt was made to eliminate visual pursuit in all of these studies, the extent of experimental control varied.

EXPERIMENT 2

Although the stimulus conditions of Experiment 1--short duration motion sequences with a steady fixation--are typical of previous experiments examining TSC, they certainly do not characterize all or even the most common conditions during simulated flight. Rather, motion sequences are usually of extended duration, and the observer typically tracks the object of interest.

The findings of Morgan and Watt (1982) indicate that both motion-sequence duration and oculomotor behavior (or some concomitant) can affect TSC. For a target velocity of 5 degrees/s and interstation distances of 4.5 or 2.25 arc min, they found that the threshold for detection of a temporal offset decreased as the duration of the stroboscopic motion sequence increased from 75 to 600 ms. (Trials during which visual pursuit occurred were excluded.) In a separate study with 150 ms sequences, they found a marked reduction in threshold when an observer attempted to track the target rather than to maintain a central fixation, even though tracking did not occur on all of the trials and, on average, was evident only during the last 10 to 15 ms of the sequence. The authors speculated that thresholds were lower when the experimental conditions favored "attentional pursuit."

Experiment 2 was designed to examine TSC under instructions to visually track the target. Motion-sequence duration was varied. The shortest sequences consisted of 8 target-component displays. If measured from the onset of the motion sequence to the onset of the mask, as was done in Experiment 1, this sequence had a duration of 133 ms. If measured from the first to the last target display, as both Burr and Morgan did in their research, the duration was 117 ms. Given the trial-to-trial variation in direction and speed of target motion, it is unlikely that pursuit eye movements could have been initiated during these presentations. In contrast, visual pursuit should have been well established during the longest sequences, which exceeded half a second (Hallett, 1986).

Two variables which could affect the latency of visual and attentional pursuit were also manipulated: the location of the fixation markers and the temporal interval between marker offset and motion sequence onset. The fixation markers were either centered, as in Experiment 1, or offset to the starting location of the following motion sequence. In the latter condition, the markers not only indicated the position of the first station but also provided information regarding the direction and speed of the following motion sequence. The fixation markers disappeared either 16.7 (no gap) or 200 (gap) ms before the onset of the motion sequence. When a point is attentively fixated, attention is said to be "engaged"; prior to moving attention to a new target, the current focus must be disengaged (Fischer & Breitmeyer, 1987; Posner, Walker, Friedrich, & Rafal, 1984). A 200-ms gap between the offset of a fixation cue and the onset of a target is thought to provide time for disengagement and has been shown to result in both faster reaction times (Posner et al., 1984) and "express saccades" with a modal latency of about 120 ms, approximately 100 ms less than the latency of a regular saccade (Fischer & Breitmeyer, 1987; Mayfrank, Mobashery, Kimmig & Fischer, 1986).

Method

Four men and 2 women served as observers. The observers were all in their 20s and had normal or corrected-to-normal vision. Although one observer had participated in the previous experiment, all were naive as to the purpose of this experiment.

The motion displays and experimental procedures were the same as those in Experiment 1, with the following exceptions: (a) Trials varied in the duration of the motion sequence (133, 267, or 533 ms), the location of the fixation markers (centered or offset to the starting position of the motion sequence), and the temporal interval between the last display of the fixation markers and the first field of the motion sequence (16.7 or 200 ms). (b) There was no trial-to-trial variation in target form, raster pattern, or image update rate. The target form consisted of a single pixel centered over a 3-pixel line, the display was interlaced, and the update rate was 30 Hz. Thus, the 2 target components were

presented at the same horizontal locations, in veridical alignment but separated by 1 field time. (As with the interlaced displays in the previous experiment, the part of the form written first was systematically varied.) (c) To reduce possible interference effects resulting from the spatial and temporal proximity of the fixation markers and the target, the former were changed from single-pixel points to 4-pixel vertical lines and their proximate end points were separated by 10 (as opposed to 5) pixels.

The observers were tested individually for 6 sessions, the first 2 of which were considered practice. Each session consisted of 1 presentation of each of the 144 possible displays (3 motion-sequence durations x 2 field orders x 2 fixation positions x 2 fixation-to-target intervals x 3 speeds x 2 directions), divided into 2 blocks according to fixation position (center vs. offset). Trials were ordered randomly within a block, and block order was counterbalanced both between and within observers.

The observers were instructed to (a) fixate the position marked by the vertical lines before initiating a trial, (b) visually track the moving target, and (c) report their final percept if the shape appeared to change while moving. The response set was expanded to include the phrases "way-off-on-the-left" and "way-off-on-the-right," which corresponded to complete TSC for the highest velocity (see Fig. 4). The "multiple-forms" response option was eliminated.

Results

Responses in Accord with Predicted Percept

Each response was initially categorized as correct or incorrect with respect to the predicted percept (as shown in Fig. 4) for the velocity and component order presented (i.e., the form created if the part written first at each location was perceived as spatially advanced by the distance it would have traveled during the 16.7 ms separating the 2 fields). These data were subjected to a repeated-measures analysis of variance (α =.01).

Figure 5 shows the percentage of responses in accord with the predicted percept as a function of motion-sequence duration and target velocity. Both main effects and the interaction were significant: Whereas predicted-percept responses were almost entirely limited to the slowest target velocity when the stimulus sequence was only 133 ms (8 vertical scans), they occurred on over 80% of the trials, for each of the target velocities, when the stimulus sequence was 533 ms.

The length of the temporal interval that separated the final presentation of the fixation markers and the onset of the moving target also had a significant effect upon the percentage of responses in accord with the predicted percept: 52% for the 200-

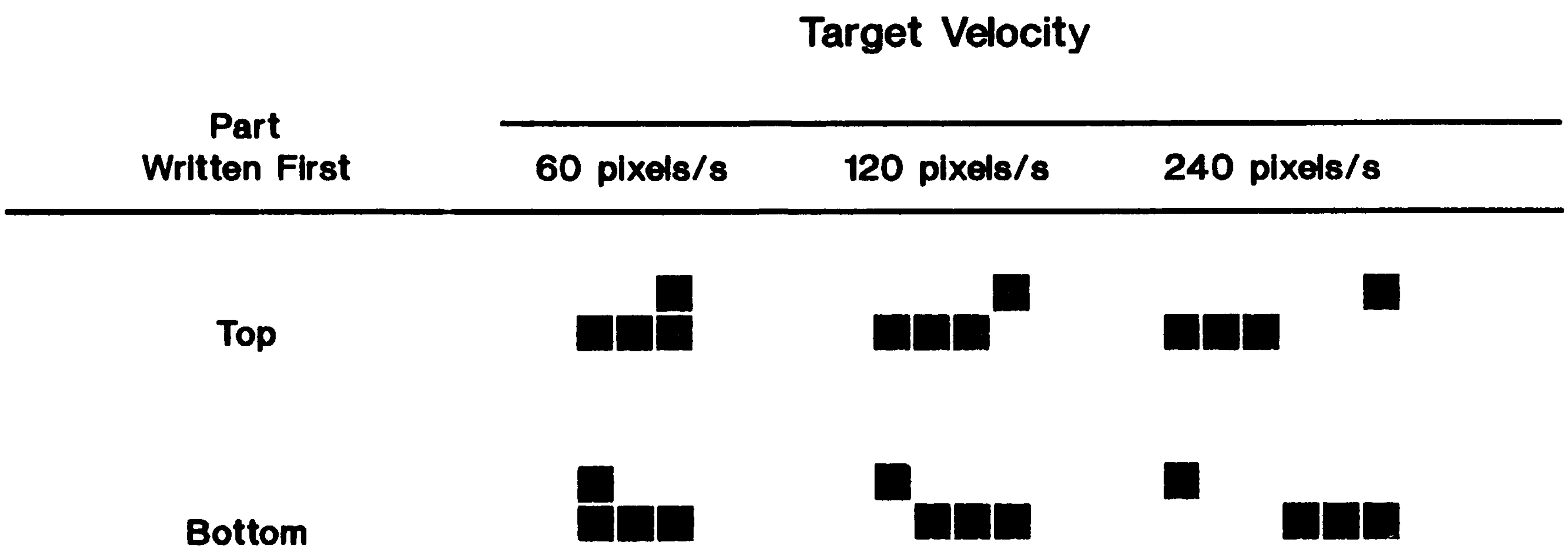

Figure 4. Predicted Percepts for Left-to-Right Motion Sequences in Experiment 2.

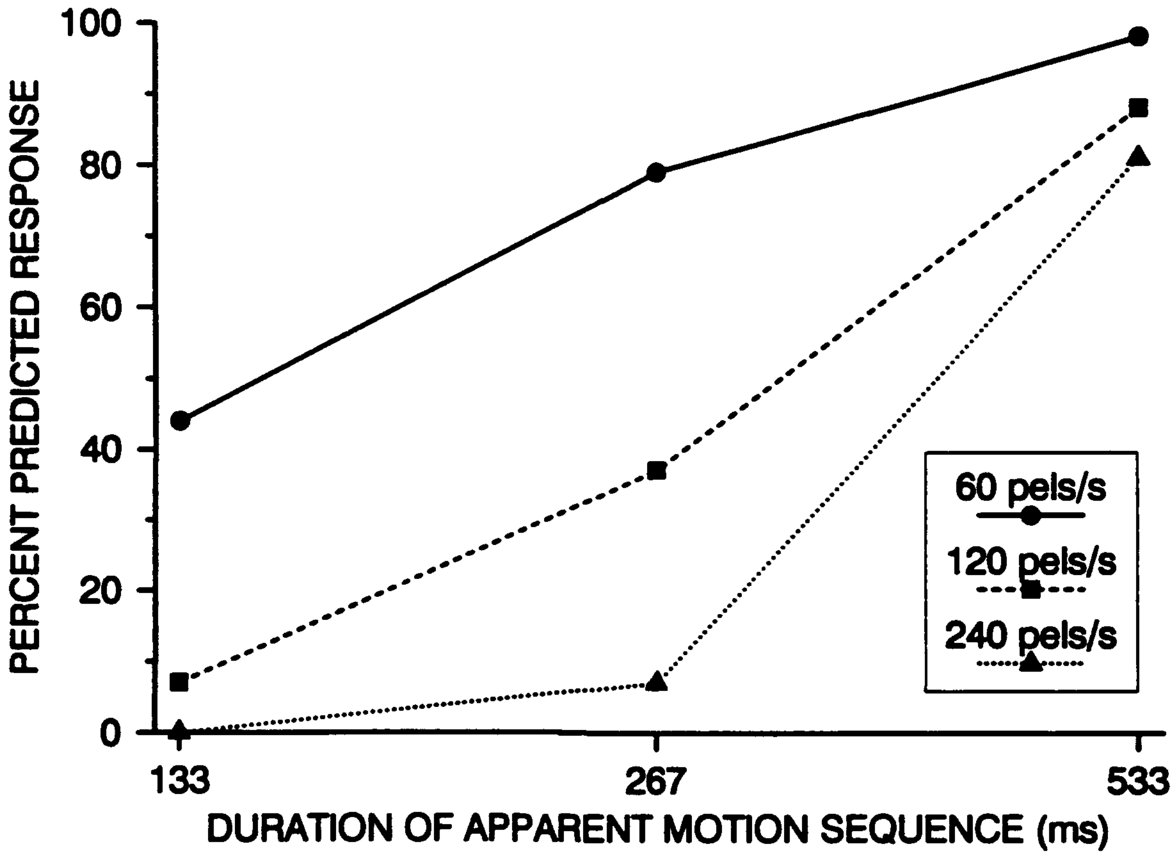

Figure 5. Percentage of Responses in Accord with the Predicted Percept in Experiment 2.

ms interval compared to 46% for the 17-ms interval. Although performance did not vary significantly with fixation location, the difference was in the expected direction (4% more predicted-percept responses when the fixation was offset than when it was centered). Finally, responses in accord with the predicted percept increased with practice. The means for the 4 test sessions were, in order, 45%, 48%, 50%, 51%.

Other Responses

In general, the percentage of *center* (target form) responses increased with the velocity of the target and decreased with the duration of the apparent motion sequence, a pattern opposite to that found for the predicted-percept responses. The sum of the predicted-percept and target-form responses never equaled 100%, however, and this sum was less than 50% for certain combinations of target velocity and motion-sequence duration. The responses that corresponded to neither the stimulus form nor the predicted percept typically represented less-than-predicted displacement in the appropriate direction. Responses corresponding to displacements against the direction of motion were rare. Reported apparent displacement was also infrequently greater than that associated with complete TSC, with one exception: For the shortest presentations of the lowest target velocity, 27% of the responses corresponded to greater-than-predicted displacement if the bottom part of the target was written first. This finding was part of a more general tendency, most evident when the duration was limited to 133 ms (8 component presentations), for displacement to be greater for bottom-first than for top-first sequences.

Discussion

The results of Experiment 2 support and extend the results of previous studies. Under instructions to track the interlaced display of a target in horizontal motion, the probability of reporting complete TSC was a decreasing function of target velocity and an increasing function of motion-sequence duration. The interaction of these 2 factors was such that the form associated with complete conversion was the predominant percept for all 3 velocities when the duration of the motion sequence exceeded half a second.

The duration and duration x velocity effects are potentially amenable to a variety of interpretations. In Fourier terms, limiting the duration of the motion sequence spreads the spatiotemporal spectrum. The deleterious effects of such spread may have been a positive function of interstation distance. On the other hand, the time available for processing and, presumably, the duration and accuracy of visual pursuit increased with sequence duration. If the available processing time was the primary factor, the pattern of results suggests that the mechanisms responsible for TSC require time for activation and that the required time increases with interstation distance or target velocity. If visual pursuit (or some concomitant) was primary, the results suggest that pursuit facilitates or provides an alternative to the conversion mechanism that operates during central fixation and that the efficacy of the primary mechanism is negatively related to the size of the inter-station distance or to the eccentricity of retinal stimulation.

If pursuit eye movements were perfectly matched to the virtual horizontal velocity of the target (and of each component-defined object), a given component would be repeatedly imaged on the same retinal locus. The arrangement of these components would correspond to that of the predicted percept, not to that of the target form. Complete TSC is thus equivalent to the composite form that would be repetitively painted on the retina if the velocity of the eyes matched the virtual velocity of the target.

The pursuit system is not, however, highly accurate (Hallett, 1986; Wetzel, 1988), and if the velocity of the eyes varied, so would the retinal arrangement of the 2 target components. Given the likelihood of this variability and the evidence that pursuit is not necessary for TSC with low velocity sequences, the consistency of conversion during pursuit is probably not attributable to direct perception of the retinal image.

EXPERIMENT 3

In Experiment 1, when the stroboscopic motion sequence was limited to 267 ms and observers were instructed to maintain a center fixation, the noninterlaced display with a 30-Hz image-update rate resulted in accurate perception of the stimulus form at all 3 target velocities. Yet, in that condition, an entire form was written twice at each displayed location, and the 2 writes were separated by a 60th of a second. If TSC had occurred, observers would have seen a double image of the target, with the 2 replicas separated by half the distance between successive displayed locations.

Hempstead (1966) reported perception of double images for motion sequences equivalent to those generated by a 30-Hz update rate and a noninterlaced display, but only if the observer visually tracked the object. He also reported that observers saw 4 moving lines if the target line was displayed 4 times at each location and the update rate was greater than approximately 14 Hz. In his investigations, the moving target was light and the surround was dark.

Method

Six young adults (4 men, 2 women) served as observers. The observers all had normal or corrected-to-normal vision and were uninformed regarding the experimental variables.

The visual displays and experimental procedures were the same as those in Experiment 2, with the following exceptions: The raster was noninterlaced, and the position of the target was updated at 60, 30, or 15 Hz. There were 4 motion-sequence durations: 267, 533, 800, and 1067 ms. To accommodate the longest duration in one horizontal pass across the display screen, the

highest target velocity was 180 rather than 240 pixels/s. Direction of target-surround contrast was varied. Because afterimages were apparent following long-duration masks with the light-on-dark displays, the mask was presented for only 200 ms. The remainder of the response period was filled by an appropriate (dark or light) blank field.

The observers were tested individually for 6 sessions; the first 3 sessions were considered practice. To simplify the classification of percepts, each session was limited to 1 target velocity. The trials within a session were blocked according to direction of contrast and, within each of these blocks, according to pretrial fixation position. Each subblock consisted of 1 presentation of each of the 48 possible displays created by all possible combinations of the remaining variables (4 sequence durations x 3 update rates x 2 fixation-target intervals x 2 directions of motion). Three of the observers started each session with light-on-dark displays and each subblock with a center fixation; 3 of the observers started with the opposite combination. During the first practice session, the target velocity was 120 pixels/s; during the second, 60 pixels/s; and during the third, 180 pixels/s. During the test sessions, 1 of the 6 possible orders of the 3 velocity conditions was presented to each observer.

Figure 6 illustrates the forms associated with complete TSC (the predicted percepts) for the image update rates and virtual target velocities used in this experiment: If each top pixel is taken to represent 1 object of a multiobject form, the number of objects in the predicted percepts equals the number, $\underline{n}$, of presentations of the target at each location (1 for 60 Hz, 2 for 30 Hz, and 4 for 15 Hz), and the spacing between objects equals the distance between displayed locations divided by $\underline{n}$.

In pilot work, observer responses indicated that they often perceived relatively smooth motion of the multiobject forms that represented complete TSC for a given velocity (see Fig. 6). Additionally, observers sometimes perceived either jerky motion of a single object or relatively smooth motion of other forms: 3 appropriately spaced objects, 1 extra-wide object, or 2 objects separated by a larger-than-appropriate spatial interval. The response set ("one," "two," "three," "four," "one-jerky," "one-wide," "two-gap," and "missing") included an option for each of these percepts. To facilitate percept classification, at the beginning of each session the observer was given a figure illustrating the multiobject spacing that was appropriate for the velocity that would be presented.

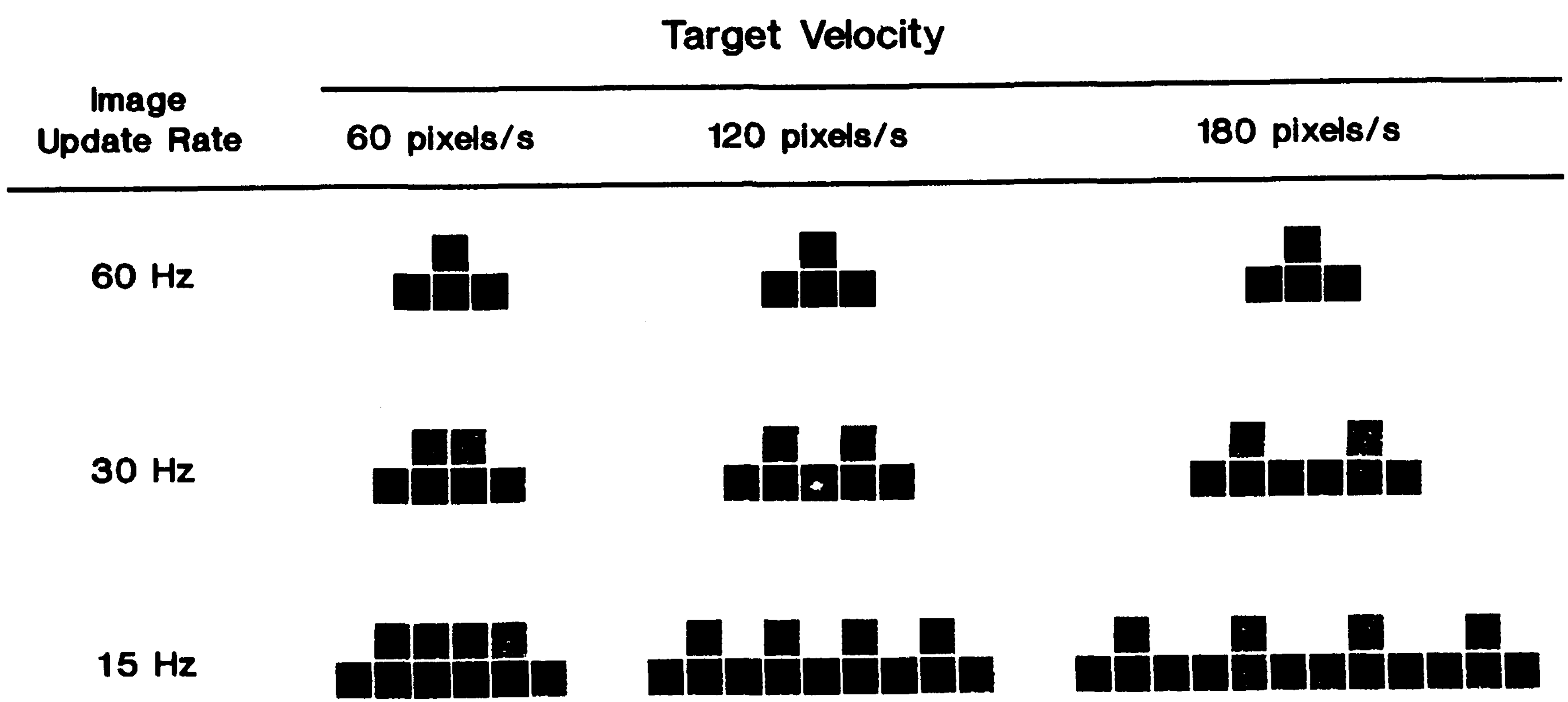

Figure 6. Predicted Percepts for the Dark-On-Light Display in Experiment 3.

Results

Responses in Accord with Predicted Percept

Each response was initially categorized as correct or incorrect with respect to the percepts depicted in Figure 6. (A response indicating jerky motion of a single object was treated as a correct response when the update rate was 60 Hz, and a response indicating 2 objects separated by a larger-than- anticipated gap was treated as a correct response when the update rate was 30 Hz.) Numerous effects were significant when these data were subjected to an analysis of variance (α =.01). Only a subset of the findings will be presented in this section; other findings will be discussed when the response distributions are described.

Figure 7 shows the percentage of responses in accord with the predicted percept as a function of sequence duration and update rate. (Both main effects and the interaction were significant.) When the update rate was 60 Hz, observers reported seeing 1 object on essentially every trial for which the sequence duration was 533 ms or greater. Although starting at a somewhat lower percentage, a similar pattern was shown for the 30-Hz update rate: Observers reported seeing the predicted percept, which in this case was 2 objects, on all but the shortest sequence. With a 15-Hz update rate, on the other hand, the predicted percept of 4 objects was almost never reported for sequences of 267 ms and was reported on only 58% of the trials with a duration of 1,067 ms.

As illustrated in the Response Distributions section, the velocity and velocity x duration effects varied significantly with update rate. Thus, to examine the effects of velocity, a separate analysis (with α = .05) was conducted for each update rate. Because of the ceiling and floor effects illustrated in Figure 7, these analyses were restricted to the 267-ms sequences for 60- and 30-Hz update rates and the 533- to 1,067-ms sequences for the 15-Hz update rate.

Velocity did not have a significant effect upon the percentage of predicted-percept responses for the 267 ms, 60-Hz sequences. The velocity effects for the lower update rates were in opposite directions: The frequency of predicted-percept responses was a decreasing function of target velocity for the 267-ms, 30-Hz sequences and an increasing function of target velocity for the longer, 15-Hz sequences. In addition, the velocity x duration interaction was significant when the update rate was 15 Hz. As the sequence duration increased from 533 to 1,067 ms, the increase in the percentage of "four" responses for the lowest velocity was less than half the increase for the 2 higher velocities.

In the overall analysis, the fixation location, duration x location, and duration x location x update rate effects were all significant. Averaged over levels of the other variables, the

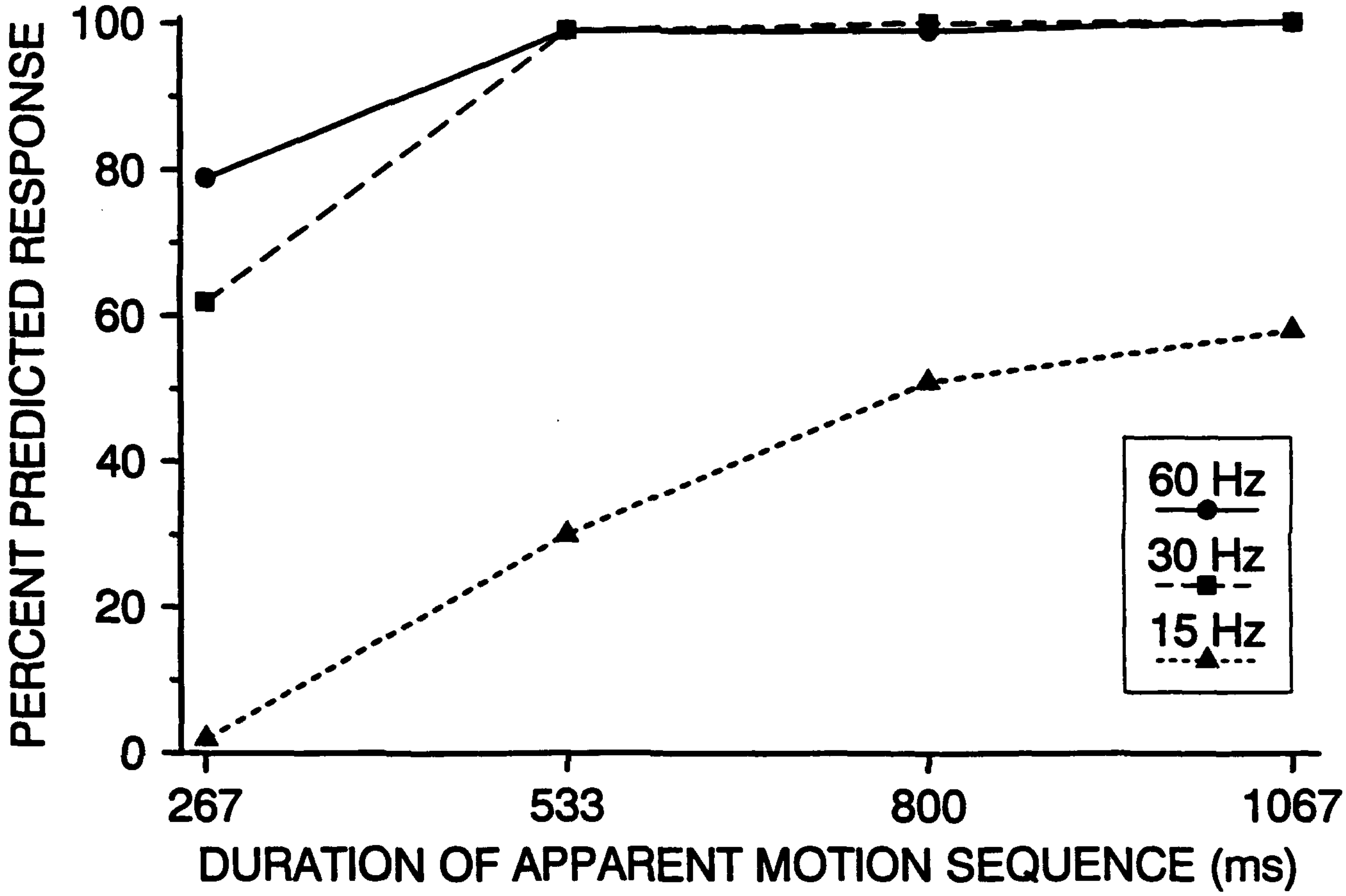

Figure 7. **Percentage of Responses in Accord with the Predicted Percepts in Experiment 3.**

percentage of responses in accord with the predicted percept was greater when the fixation markers were appropriately offset than when they were centered. For the 60- and 30-Hz update rates, evidence of a fixation effect was, of course, limited to the shortest motion sequence and reached statistical significance only in the analysis of the 30-Hz sequences. For the 15-Hz update rate, the fixation effect was limited to the 533-ms sequences.

The gap x duration interaction was also significant. Inspection of the data indicated that the effect resulted from differences, in favor of gap presence, for the 2 higher update rates when the duration was 267 ms. There was no evidence of a gap effect for the 15-Hz update rate at any sequence duration. In

subsequent analyses, the only statistically significant ($p < .05$) gap effect was for the 30 Hz, 267-ms sequences.

Response Distributions

In the analysis of the percentage of responses in accord with the predicted percept, the main effect of direction of contrast and the first- and second-order interactions of direction of contrast, image update rate, and motion-sequence duration were all significant. Consequently, the response-distributions are presented separately for the 2 contrast conditions.

As shown in Figure 8, direction of contrast significantly affected form perception for the 267-ms motion sequences in which target position was updated at 60 Hz: When the target was dark and the surrounding display was light, observers almost always reported seeing 1 object moving smoothly; when the target was light and the surround was dark, "two" responses were quite frequent.

Figure 9 presents the distributions of reported percepts for the 267-ms sequences with a 30-Hz image update rate. In the analysis of the percentage of predicted-percept responses (i.e., "two" responses) for this combination of update rate and duration, none of the effects involving direction of contrast were statistically significant. It will be recalled, however, that the velocity, fixation location, and gap effects were all significant. There was a tendency ($p < .10$) for both the velocity and gap effects to be larger with the light-on-dark than with the dark-on-light displays. Moreover, most reports of jerky motion were for the light-on-dark displays.

As shown in Figure 10, when the image update rate was 15 Hz and the duration of the motion sequence was limited to 267 ms, observers usually reported seeing only 1 object, frequently in jerky motion rather than in smooth motion. The one exception to this generality was for the light-on-dark displays of the slowest velocity. In that case, over 60% of the responses were either "two" or "three." The few responses indicating complete TSC were restricted to the 2 higher velocity, light-on-dark displays.

For the 533 ms, 15-Hz sequences, more objects were perceived for the light-on-dark displays than for the dark-on-light displays (see Fig. 11). In addition, there was a strong positive relationship between the perceived number of objects and the velocity of the target.

As shown in Figure 12, the direction-of-contrast and velocity effects remained strong at the longest sequence duration: Observers reported seeing 4 objects on less than 5% of the trials when a dark target moved at the lowest velocity, whereas they reported seeing 4 objects on over 95% of the trials when a light object moved at the highest velocity.

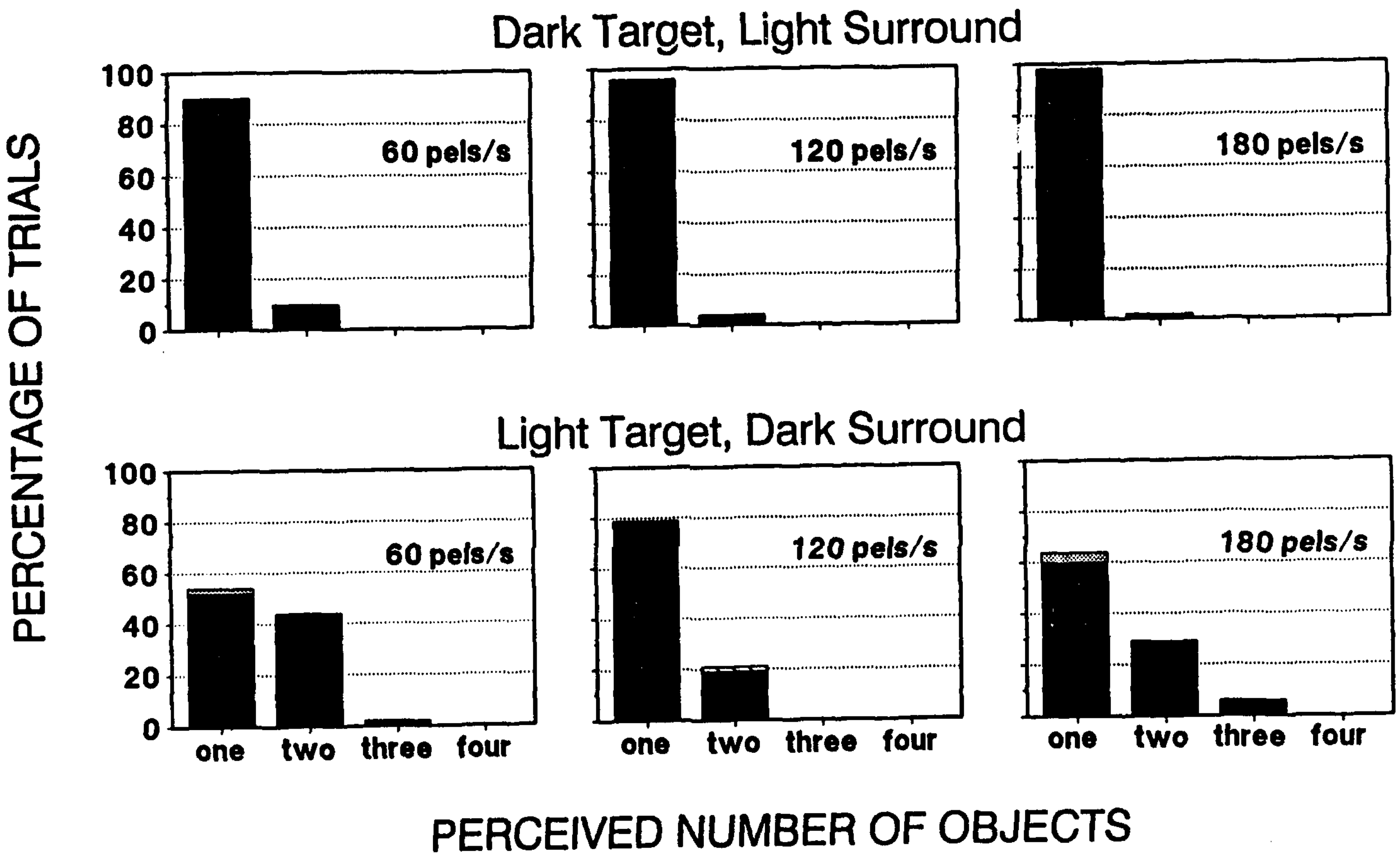

Figure 8. Response Distribution for the 267-ms Motion Sequences with a 60-Hz Image Update Rate in Experiment 3. The solid bars represent unqualified number responses. The stippled bars represent "one-wide" responses; the striped bar represents "two-gap" responses.

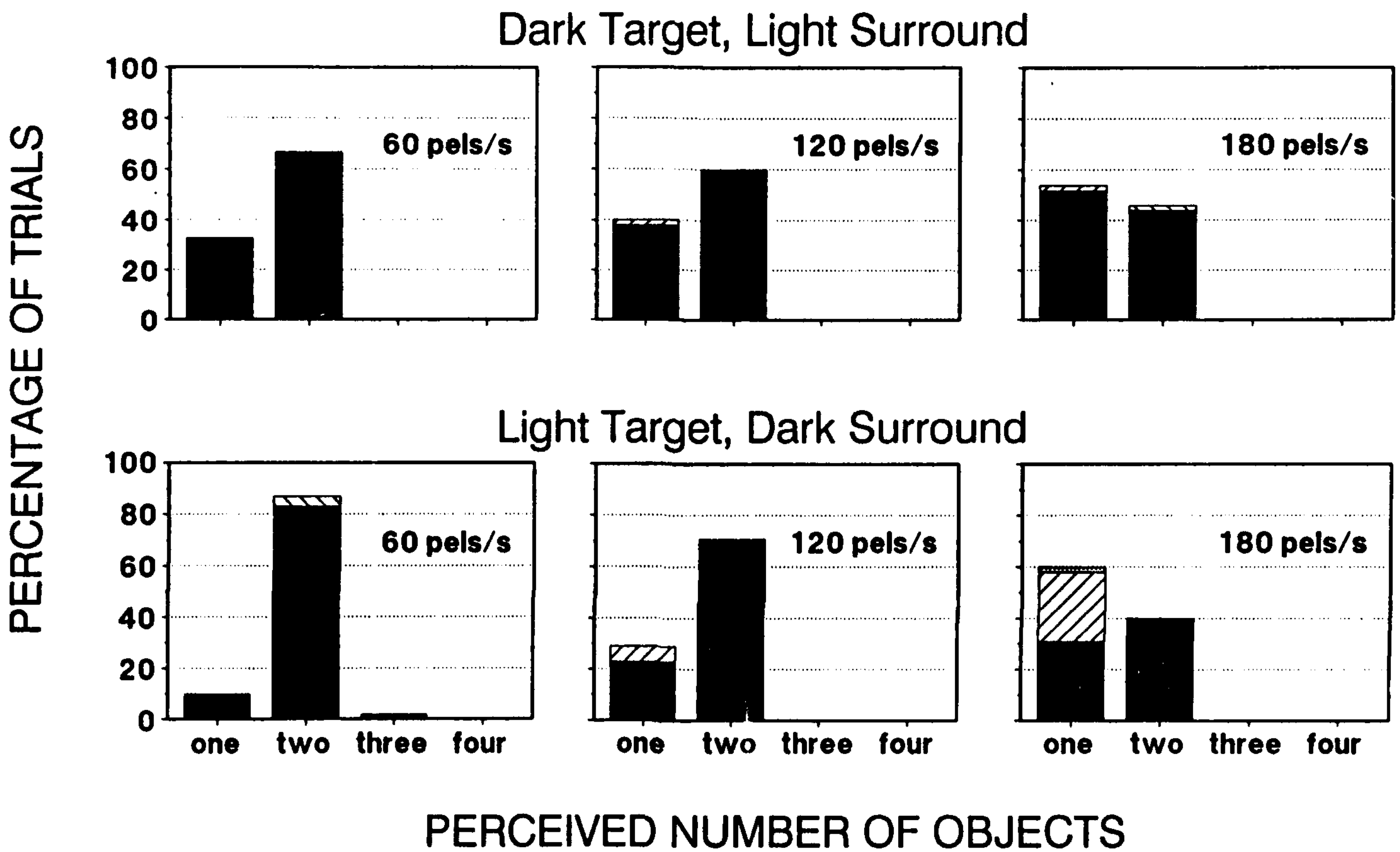

Figure 9. Response Distributions for the 267-ms Motion Sequences with a 30-Hz Image Update Rate in Experiment 3. The solid bars represent unqualified number responses. The stippled bar represents "one-wide" responses; the striped bars, in the "one" and "two" positions, represent "one-jerky" and "two-gap" responses, respectively.

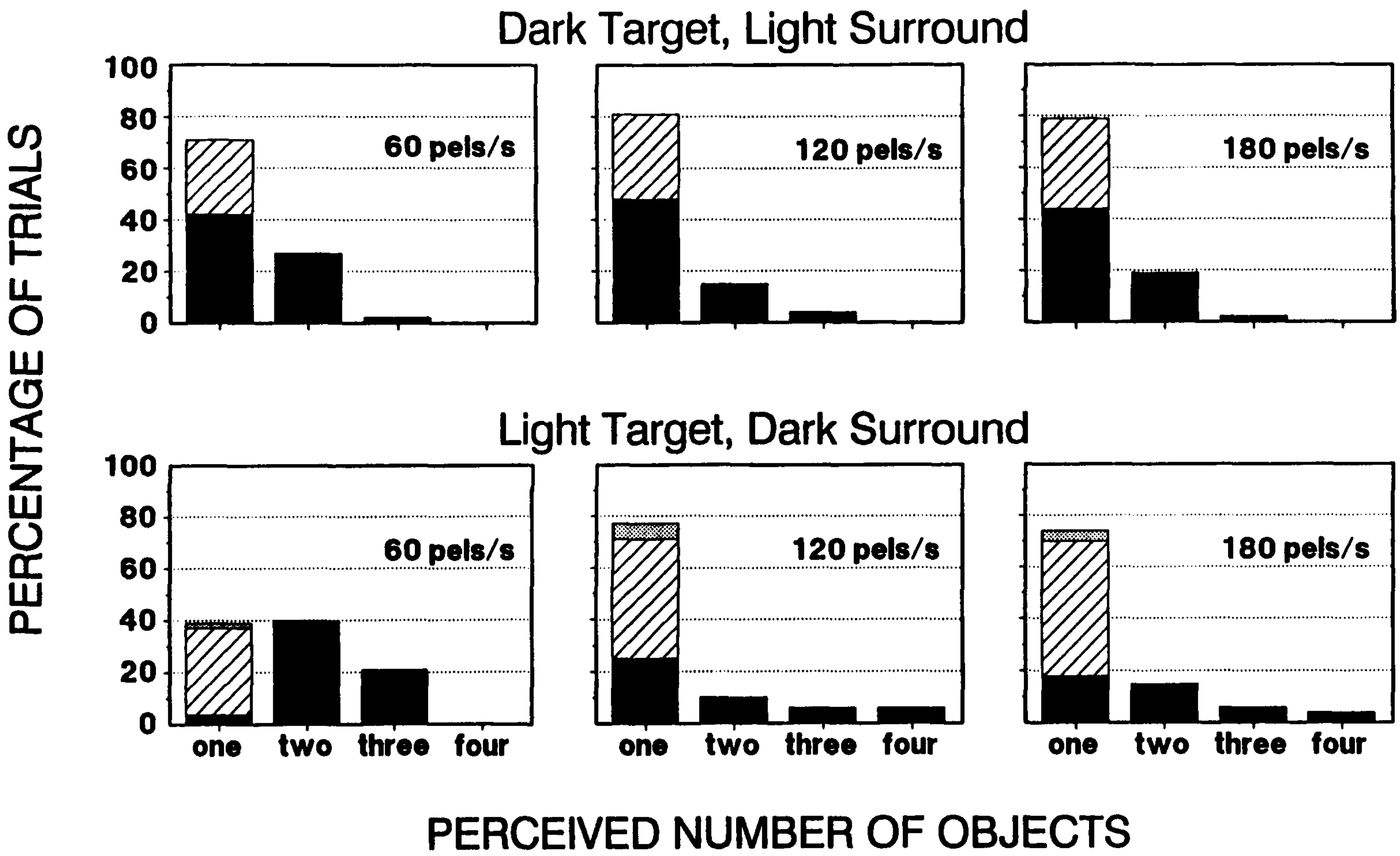

Figure 10. Response Distribution for the 267-ms Motion Sequences with a 15-Hz Update Rate. The solid bars represent unqualified number responses. The striped bars represent "one-jerky" responses; the stippled bars represent "one-wide" responses.

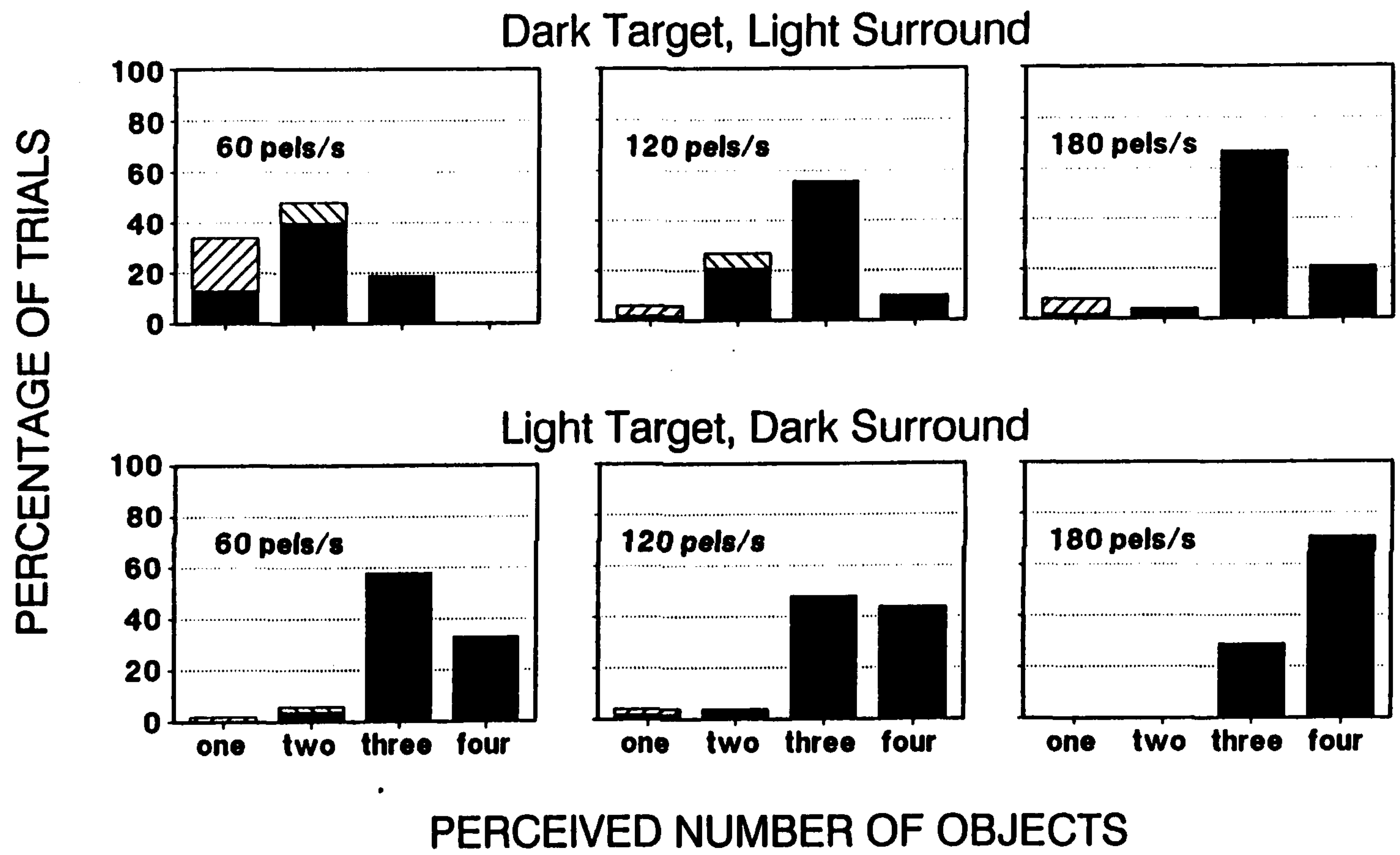

Figure 11. Response Distribution for the 533-ms Motion Sequences with a 15-Hz Image Update Rate in Experiment 3. The solid bars represent unqualified number responses. The striped bars, in the "one" and "two" positions, represent "one-jerky" and "two-gap" responses, respectively.

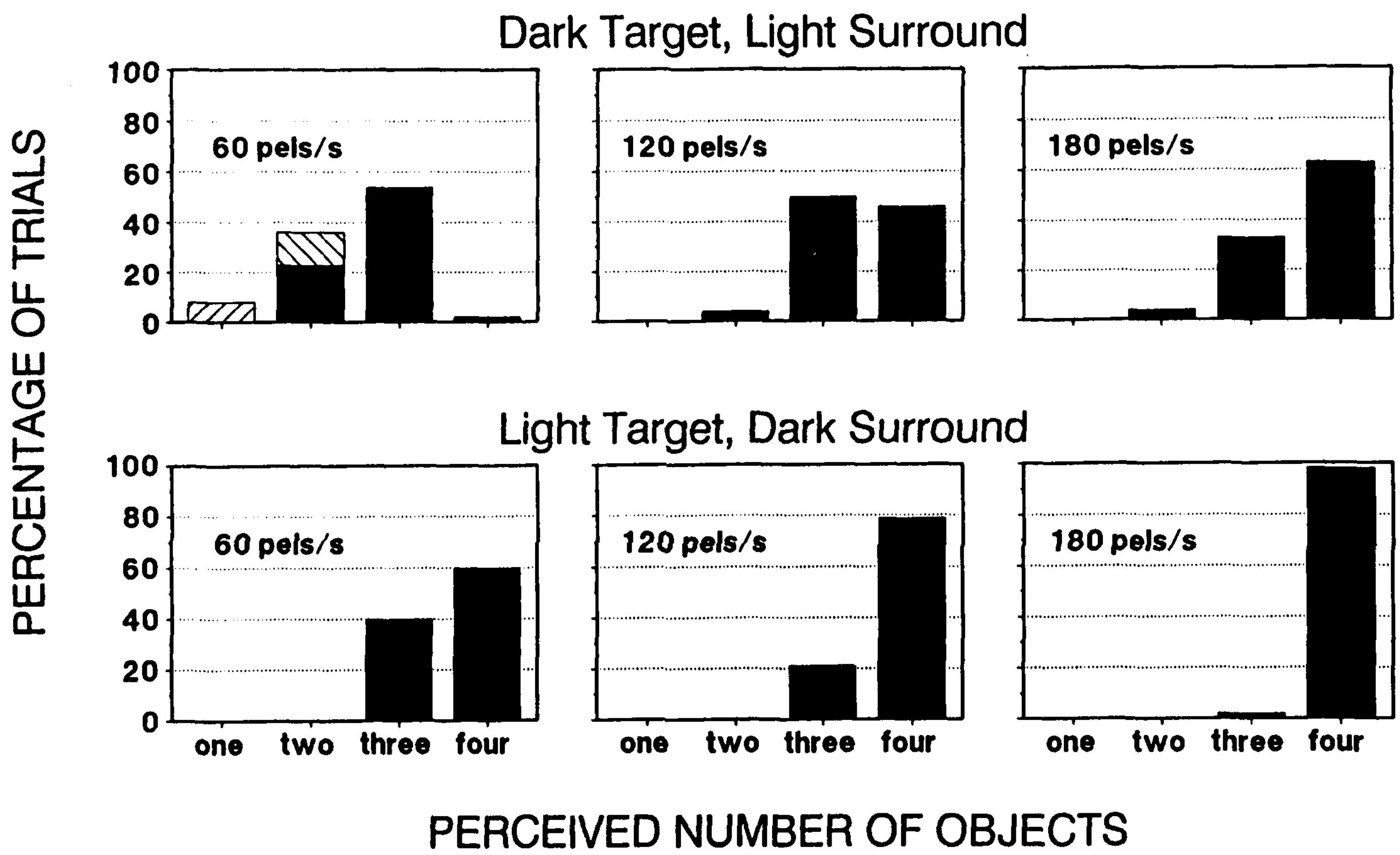

Figure 12. Response Distribution for the 1067-ms Motion Sequences with a 15-Hz Image Update Rate in Experiment 3. The solid bars represent unqualified number responses. The striped bars, in the "one" and "two" positions, represent "one-jerky" and "two-gap" responses, respectively.

Other Perceptual Effects

Although systematic data were not collected, it should be noted that the apparent figure-ground contrast of a multiple-object percept was lower than that of a single-object percept. This contrast reduction was mitigated in the areas where the component forms overlapped. Consequently, the composite forms for the 2 lower velocities were not of uniform brightness (see Fig. 6).

These effects were much more pronounced for the dark-on-light displays than for the light-on-dark displays. Moreover, the apparent contrast of the fully extended 15-Hz percept (i.e., 4 objects) was not obviously less than that of the fully extended 30-Hz percept (2 objects). Rather, the 15-Hz dark-on-light form appeared to flicker.

Discussion

The results of Experiment 3 indicate that TSC is not limited to stroboscopic motion sequences in which successive stimuli occupy different display locations. For conditions that favored visual pursuit, temporal intervals between environmentally overlapping presentations tended to be seen as spatial intervals. This general finding held for update rates as low as 15 Hz (i.e., for as many as 4 presentations distributed over a temporal interval of 67 ms), although the extent of conversion varied complexly with update rate, direction of contrast, target velocity, and motion-sequence duration.

The Role of Pursuit Eye Movements

When TSC was complete, the spatial percept corresponded to the image that would have been repetitively "painted" on the retina if the observer's pursuit eye movements had perfectly matched the defining velocity of the motion sequence. As argued in the preceding discussion section, however, inaccuracies in pursuit would result in variation in the spacing between the components of a composite form as well as in the retinal locus of a particular component. TSC during tracking probably cannot be attributed to direct perception of the retinal image.

Regardless of tracking accuracy, however, pursuit eye movements would have caused the multiple presentations at a given environmental location to be imaged on nonoverlapping, or only partially overlapping, retinal locations. Perhaps successive presentations must stimulate different photoreceptors for TSC to occur. The absence of reports of double images for the 30 Hz, noninterlaced sequences in Experiment 1 is consistent with this possibility. On the other hand, the pattern of results for Experiment 3 provides some evidence to the contrary. For the 267-ms 30-Hz sequences, the frequency of "two" responses was a decreasing function of target velocity. In addition, for the 267-

ms 15-Hz sequences, only the low velocity, light-on-dark sequences resulted in a majority of multiobject percepts. Thus, TSC and target velocity were negatively related for these brief displays, as they have been in research in which successive presentations did not overlap and eye movements were prohibited. Unless pursuit latency varied with condition, such that more than 1 object was perceived if and only if pursuit had been initiated, the data suggest that pursuit eye movements are either not necessary or not sufficient for TSC to occur during observation of motion sequences in which successive target presentations are superimposed.

Visible Persistence

Multiple forms. For the longer duration, 15-Hz sequences, when visual tracking should have been well established, the perceived number of objects increased with target velocity. In previous research as well as in the 30-Hz update conditions of this experiment, however, the extent of TSC was a decreasing function of target velocity (or interstation distance). Therefore, although it is possible that TSC actually increased with target velocity when the update rate was 15 Hz, it seems more likely that the percept for this update rate was not determined solely by TSC. In order for all components of a 4-object percept to have appeared simultaneously and continuously present, the percept resulting from each target presentation would have had to persist for at least 67 ms. Although this period is well within estimates of the duration of "visible persistence" (Coltheart, 1980), persistence is subject to suppression by subsequent presentations of spatially proximate stimuli (Breitmeyer, 1984; Di Lollo & Hogben, 1987). Such inhibitory effects increase with retinal proximity and should therefore have been greater for low velocity targets than for high velocity targets: If pursuit eye movements were roughly matched to the virtual velocity of the target, the retinal distance between successive target presentations would have increased with target velocity. Thus, responses indicating less than complete TSC (e.g., "two" or "three") may have resulted from lateral inhibitory processes rather than incomplete TSC.

Differences in visible persistence may also have contributed to the direction-of-contrast effects for the longer 15-Hz sequences. Persistence duration has been shown to decrease (Haber & Standing, 1970) and inhibitory interactions to increase (Ikeda, 1965) with increases in adapting luminance. Moreover, besides any interference resulting from subsequent target presentations, the surround in the dark-on-light sequences may have served as a masking stimulus: The retinal area on which the target was imaged during 1 presentation would have been stimulated by the light surround during each of the other 3 presentations. The relatively low contrast and nonuniform brightness of the percepts for the dark-on-light displays suggest the operation of integrative rather than or in addition to interruptive processes (Auerbach & Coriell, 1961).

Motion Smear. For the 60-Hz update rate, successive target presentations were always separated by the distance the target would have traveled during the intervening temporal interval. Consequently, the predicted percept was a single, moving object. In accord with this prediction, observers consistently reported seeing only one object when the duration of a 60-Hz sequence was 533 msec or greater. For the light-on-dark (and, to a lesser extent, the dark-on-light) 60-Hz sequences, however, observers frequently reported seeing 2 objects when the duration was 267 ms. These responses suggest that the target sometimes appeared to be simultaneously present at 2 displayed locations.

Such a percept could have resulted from visible persistence. Indeed, given that estimates of the duration of persistence are usually in excess of 100 ms (for a brief, stationary stimulus), one might expect the target to appear simultaneously present at numerous locations (6 for a 60-Hz display and persistence of 100 ms). However, percepts consistent with persistence of this duration were never reported for the 267-ms 60-Hz sequences, and there was no evidence of persistence for the longer 60-Hz sequences. As noted by Burr (1980), a comparable lack of "motion smear" is found for targets in continuous motion.

Burr (1980) and Di Lollo and Hogben (1985; Hogben & Di Lollo, 1985) assessed the duration of visible persistence (motion smear) for stroboscopic-motion sequences. Using light-on-dark sequences and, in most cases, instructions to maintain a steady fixation, they found that such smear was reduced or eliminated for longer motion sequences. With the 200-Hz update rate used in their research (and velocities of 5 to 15 degrees/s), decreases in the apparent length of the target (i.e., in the number of locations visible simultaneously) began with motion-sequence durations of 40 to 80 ms.

Burr and his colleagues (Burr, 1980; Burr et al., 1986) have proposed that the absence of motion smear as well as the "interpolation" effect (their term for the TSC observed with vernier acuity targets) can be accounted for by the activation of motion detectors with receptive fields that are elongated in space-time according to the detector's preferred velocity. Similarly, Fahle and Poggio (1981), Morgan (1980), and Morgan and Watt (1983) have proposed that spatiotemporal filtering mechanisms can account for both interpolation (TSC) and the absence of motion smear. In contrast, Di Lollo and Hogben, (1985; Hogben & Di Lollo, 1985) have argued that motion smear is actively suppressed by lateral inhibitory processes resulting from subsequent target presentations (cf., Farrell, Pavel & Sperling, 1990).

None of these explanations can account for the pattern of results for the 267-ms, 60-Hz sequences (Fig. 8) in Experiment 3. Although the direction-of-contrast effect was consistent with expected differences in the strength of inhibitory processes,

suppression would be expected to decrease as velocity increased. On the other hand, if reports of 2 or more objects are taken to represent a failure of TSC, one would have to conclude that TSC mechanisms are activated more quickly by dark-on-light displays than by light-on-dark displays. Whereas there is no strong evidence to the contrary, the low velocity 267-ms sequences for the slower update rates resulted in more TSC when the presentation was light on dark than when the presentation was dark on light. Moreover, an account based on TSC, like one based on lateral inhibition, would predict a negative relationship between the frequency of "one" responses and target velocity.

Some or all of the reports of more than 1 object for the light-on-dark, 267-ms, 60-Hz sequences may have resulted from phosphor persistence rather than from visible persistence. The threshold for detection of such persistence would be expected to vary with a number of factors, including the level of light adaptation and the proximity and loci of the object representations in the retinal image. If reports of more than 1 object for the 60-Hz sequences did represent detection of phosphor persistence, the pattern of results suggests that distance-dependent differences in simultaneous masking were relatively unimportant and that the increase in light adaptation during the longer motion sequences was sufficient to reduce sensitivity to the point that phosphor persistence was no longer visible (resulting in consistent reports of only 1 object).

GENERAL DISCUSSION

The TSC found for vernier acuity targets has been taken by other investigators to represent "interpolation" (e.g., Burr, 1979; Fahle & Poggio, 1981; Morgan, 1979). As stated by Burr (1979), this effect is thought to show "that not only do stroboscopically illuminated targets appear to move smoothly from one stop to the next, but also, in between illumination, they are seen to occupy positions in between those where they are actually exposed (p. 835)." Similarly, according to Morgan (1979), the apparent spatial offset of the 2 line segments suggests "that the momentary position of an apparently moving target is not its most recently presented actual position, but its interpolated position (p. 491)." Although the mechanisms that have been proposed to account for this phenomenon have differed somewhat (see Burr et al., 1986; Fahle & Poggio, 1981; Morgan & Watt, 1983), all have involved some form of spatial and temporal filtering whereby the visual system removes the frequencies introduced by the sampling process.

Clearly, however, if an interpolation process is responsible for TSC, it is not interpolation between successive positions of a spatial form. For example, in previous research using acuity targets, the individual line segments were not perceived as a

single target with vertical as well as horizontal movement, as would have been the case if interpolation had occurred between successive presentations. Nor were the partial object representations in successive displays of the interlaced sequences of Experiments 1 and 2 seen as complete objects following a zigzag path. Finally, when TSC occurred for the 15- and 30-Hz sequences of Experiment 3, the percept was not in accord with interpolation between successive target presentations: The target was not seen to move horizontally with a velocity that alternated between zero and *n* times the nominal velocity.

In general, if a temporal sequence of spatial forms is to be perceived as an object in motion, the visual system must establish the *phenomenal identity* (Ternus, 1938) or *correspondence* (Ullman, 1979) of successive representations. Assuming conditions that support TSC, the results of the present research suggest (a) that the visual system extracts a constant velocity vector (cf., Fahle & Poggio, 1981) by means of processes which integrate information over a temporal interval in excess of 100 ms and (b) that this velocity vector determines correspondence--and thus the form and motion percepts associated with a given stroboscopic display. Accordingly, in previous research with acuity targets and in the noninterlaced displays of Experiment 1 and 2, correspondence was established between successive presentations of a given component. In Experiment 3, correspondence was established between successive presentations of the target only when the image update rate equaled the display rate. When the update rate was less than the display rate, correspondence was established between presentations separated by the update interval. For example, when the update rate was 15 Hz, correspondence was not between forms separated by 16.7 ms but between forms separated by 66.7 ms. TSC, from this perspective, is a failure of the visual system to register short-term fluctuations in velocity.

CONCLUSIONS

In computer-image generation systems, the spatiotemporal representation of a moving object depends upon the update (sample) rate of the IG and the raster pattern and refresh rate of the display device. The results of this research indicate that various representations are not perceptually equivalent. Perception of object motion is accompanied by a tendency to perceive temporal intervals as spatial intervals. Such TSC, which supports accurate form perception when the update rate of the IG equals the refresh rate of the display device, results in inaccurate form perception when the update rate is less than the refresh rate.

Nonveridical form perception will occur during simulated flight if the refresh rate of the display device is greater than the update rate of the IG and if TSC occurs. The specific nature of the perceptual aberration will depend upon numerous factors, including the resolution and raster pattern of the display; the

spatial sampling procedure used to determine the content of a particular pixel; the size and complexity of the object representation; and the speed, direction, and duration of object motion. In general, if an object is moving at a constant velocity and TSC is complete, the earlier representations will appear spatially advanced by the distance they would have traveled if they were moving at the object's velocity. Thus, for the stimulus forms and velocities presented in this research, observers perceived either multiple replicas of the object (when the display was noninterlaced) or a distortion of object form (when the display was interlaced). For larger object representations and lower velocities, the object form should appear smeared in the direction of motion.

If the update rate equals the refresh rate and the display is interlaced, a failure of TSC can result in nonveridical form perception: The parts of the form presented in the 2 fields will not be seen in proper alignment unless conversion occurs. It is not possible to simultaneously track all of the moving elements in complex, dynamic scenes. Thus, to the extent that pursuit eye movements are necessary, TSC may fail at relatively low velocities during simulated flight.

To minimize the likelihood of perceptual aberrations during simulated flight, the update rate of the IG should equal the refresh rate of the display device and the display should be noninterlaced. Such a system would be expensive, however, and further research will be needed to determine whether the improvement in perceived-image quality results in a significant improvement in training capability.

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